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CALCULATIONS OF THE EFFECTS OF LOCAL FLUX DISTORTIONS IN CENTRAL REACTIVITY WORTH MEASUREMENTS IN ZPR-6 ASSEMBLY 7*

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ABSTRACT

Central reactivity worth measurements are usually analyzed with a first-order perturbation theory formulation that neglects the effects of local flux distortions introduced by the experimental configuration on the measured worths. In this report, the reactivity effects of these distortions, for the small-sample and unit-cell measurements in ZPR-6 Assembly 7, are investigated with use of a perturbation, integral transport formulation to determine if they contribute appreciably to the discrepancies between theory and experiment that have been observed in this class of measurements.

The results of these calculations indicate that for most samples the reactivity effect of flux distortions is small, 5% or less, and therefore cannot account for the discrepancy between theory and experiment in the worths of fuel materials. For the fissile samples a small self-multiplication effect was computed, which in the radial sample changer was compensated for by the slight flux depression in the sample tube. The flux distortion effect appears to be largest in highly absorbing material and light, scattering material samples.

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I. INTRODUCTION

Reactivity worth measurements are usually analyzed with use of a first-order perturbation theory (FOP) and with the assumption that the samples and any associated structure do not distort the fluxes in the vicinity. The purpose of the study described in this report is to examine the validity of this method and to assess the magnitude of the effect on central reactivity worths of local flux distortions.

In ZPR-6 Assembly 7,[1-3] a large, uniform, mixed plutonium-uranium oxide critical assembly, constructed as part of the Demonstration Reactor Benchmark Critical Assembly Program,[4] central reactivity worths were measured with two techniques as described in Ref. 5. Measurements of the worths of small cylindrical and annular samples contained in a holder were made in the in the radial sample changer (RSC),[6] a long double-walled thin stainless steel tube. These will be referred to as the small-sample measurements. The other measurements, made with the axial sample changer (ASC)[7] were designed to measure the worths of the individual core constituent materials in their normal plate environment by measuring the worth of removing individual plates from the unit cell. These measurements will be referred to as the unit-cell measurements.

The perturbation, integral-transport theory code, PIT,[8] was used to analyze these experiments. PIT considers a cell consisting of the test zone surrounded by a portion of the core. A successive-generation, integral-transport calculation is made of the distorted real and adjoint fluxes in the cell (if the cell were composed solely of core material, the fluxes would be undistorted). Then the test zone is perturbed and the reactivity worth of the perturbation is computed either with recalculation of the real flux distributions, exact perturbation theory (EP), or without recalculation of the real flux distributions, FOP. Also the worth of the perturbation using undistorted fluxes is computed.

II. ANALYSIS OF SMALL-SAMPLE REACTIVITY MEASUREMENTS

The central worths of 30 samples having a variety of compositions were measured with use of the RSC. A description of these samples and their measured worths is given in Ref. 5 (the diameter of the boron sample is 0.3175 cm not 0.125 cm). The samples have either an outer diameter of approximately 2.13 cm or 0.99 cm. Therefore in the PIT calculations two reference configurations, as described in Tables I and II, are used. These configurations approximate reasonably well a cross section through the RSC at the elevation of the sample. The low density stainless inside the sample holder accounts for the extra steel on the ends of the sample holder. The perturbations from which the sample worths were obtained are described in Table III.

The results of the calculations and the experiments for the small-sample worths in the RSC are given in Table IV. The experimental results are given for measurements in the normal plate core environment and in the central match plate zone environment. The calculational results are given for three cases: first order perturbation theory using undistorted real and adjoint fluxes; first order perturbation theory using distorted real and adjoint fluxes; and exact perturbation theory which by definition uses distorted adjoint fluxes and distorted and perturbed real fluxes. The undistorted fluxes were the central fluxes obtained from one-dimensional diffusion calculations in which Assembly 7 was represented as a cylinder and in which the core cross sections were corrected for cell-heterogeneities and, if appropriate, resonance self-shielding. In the diffusion calculations the chi vector was that of core material.

In the PIT calculations, the same heterogeneous core cross sections were used as in the diffusion calculations and homogeneous cross sections were used for the test zone except for the two tantalum samples, for which shielded cross section derived for the measurements in ZPPR Assembly 2 were used.[9] For the natural boron sample ^{11}B was represented by carbon; for the plutonium samples ^{242}Pu was represented by ^{240}Pu and the small amounts of ^{241}Am were neglected; and for the enriched uranium sample the ^{234}U and ^{236}U were neglected. In the PIT calculations the chi vector of ^{239}Pu was used for all fissile samples. A period-reactivity conversion factor of 1035 Ih/% $\Delta k/k$ was used as well as ENDF/B version 1 data in the 'Idaho' dataset developed for ZPPR Assembly 2.

From Table IV it is seen that generally the calculations overpredict the worth of the samples. This overprediction is most severe for the molybdenum, boron, uranium and plutonium samples. Comparison of the two first-order perturbation results gives the effect of the flux distortions introduced by sample tube and sample holder. The adjoint fluxes are depressed by 0-2% in all groups and the real fluxes are depressed slightly at high energies and increased slightly at low energies. These distortions result in reductions of from 1 to 7% in the worth of the samples and generally improve slightly the agreement between calculation and experiment.

Comparison of the first-order perturbation with distorted fluxes results with the exact perturbation results gives the effect, on a broad group basis, of absorption, self-multiplication, and multiple scattering in the sample on its worth. From the Table it is seen that for the fissile samples because of self-multiplication there is an increase in worth of a few percent from the sample size effect. These results are consistent with the analysis of sample size effects in plutonium worth measurements in ZPPR Assembly 2, in which a simpler theoretical model was used.[10] For the constituent of stainless steel and aluminum and sodium, the sample size effects are small, but for highly absorbing materials, tantalum in sample TA-2 and boron, the depletion of the low energy real flux caused a 4-9% loss

in worth. The largest sample size effect was in carbon where a softening of the spectrum resulted in a 10% decrease in the carbon sample worth (a similar result was computed for the carbon sample in ZPPR Assembly 2).

Table IV also gives the ratio of the worths calculated with exact perturbation theory and with simple first-order perturbation theory. For the fissile samples, the net flux distortion effect is quite small (about 1%). For structural materials the flux distortion effect is about 4% but for light scattering materials (carbon and sodium) and the larger tantalum sample, the effect is large 10-15%.

When the sample worths computed here with first-order perturbation theory and undistorted are compared with those given in Ref. 5, it is noted that although worths of non-fissile materials are identical there are discrepancies of a few percent for fissile samples. For example, the ^{239}Pu worth inferred from the worth of sample MB-10 is about 198 Ih/kg whereas Ref. 5 gives 205 Ih/kg. The computations are identical except in the chi vector used in the perturbation calculations. Here the chi vector was that of ^{239}Pu with ENDF/B data while in the earlier calculations the same chi was used in the perturbation calculations as in the diffusion calculations from which the fluxes were generated, that of Assembly 7 core material with Keepin neutron yield data.[11] It should be noted that the chi effect appears to be larger for these fissile samples than the flux distortion effect.

III. ANALYSES OF UNIT CELL REACTIVITY MEASUREMENTS

The unit cell substitution experiments were analyzed with the cell given in Table V as the reference configuration. This reference configuration is based on the unit cell used to compute all hetergeneity effects[12] and differs from that cell in that the stainless steel cladding is homogenized into the fuel plate (which has 21.155 gm of Pu/U/Mo missing to mock up the fuel plate with the empty tunnel used in the measurement) and with the addition of homogenized core material on both sides of the unit cell.

The computed material worth were obtained from exact perturbation calculations for the unit-cell substitutions given in Table VI. For the core material, cross sections corrected for cell heterogeneities were used. Because the PIT formulation accounts for cell heterogeneities, homogeneous cross sections, with ^{238}U and the isotopes of plutonium resonance shielded were used for the plates in the unit cell. To have used heterogeneous cross sections for the plates in the unit cell would result in cell heterogeneities being corrected for twice. In the fifth perturbation, the sodium-out uranium and plutonium were obtained from sodium-voided MC^2 runs. A more prescription for these unit-cell substitutions would have been to modify to sodium-in cross sections for increased resonance shielding in the sodium-voided

unit cell. ^{238}U in depleted uranium was taken to have resonance shielding of uranium in the fuel when placed in the tunnel in the fuel plate and was assumed to have the resonance shielding of uranium in the U_3O_8 plate when in the 1/8-in. plate next to the U_3O_8 plate.

The results of the calculations along with the experimental results are given in Table VII. The material worths of Fe, Fe_2O_3 and stainless in the environment adjacent to the Pu/U/Mo fuel plate were obtained from perturbations 6-8. From perturbations 6 and 8 the worths of Fe_2O_3 and SS are obtained. With the worth of Fe_2O_3 known, the worth of Fe is obtained from perturbation 7 and with the worth of SS known, the worth of ^{239}Pu is obtained from perturbation 1. Similarly, the worths of U_3O_8, depleted uranium and SS in the environment near the matrix are obtained from perturbations 9-11.

Also included in Table VII are first-order perturbation results obtained with distorted fluxes. These FOP results should be equivalent to FOP results obtained with undistorted fluxes and heterogeneous cross sections, since weighting the homogeneous, resonance-shielded cross sections by the distorted fluxes for the reference configuration should yield the heterogeneous cross section. From Table VII from comparison of the first-order and the exact perturbation results, a 5% increase in worth of the fissile ^{239}Pu and Pu/U/Mo worths is observed in agreement with the results of small-sample analysis. For the sodium and structural material substitutions, there is little difference between the FOP and EP results except for Fe_2O_3. For the sodium substitution, the use of sodium-out cross sections for uranium and plutonium, has a significant effect by improving C/E by 15%.

IV. CONCLUSION

From this analysis of small-sample and unit-cell substitution reactivity experiments, it is clear that local flux distortion effects do not account for the discrepancies between theory and experiment that have been observed for this class of experiments. The sample tube and sample holder tend to depress the fluxes slightly which has a reactivity effect of a few percent on the calculated worth of the small-samples. For the fissile small-samples, self-multiplication compensates for this effect. Only for the light scatterers and highly absorbing materials do the flux distortions affect the calculated worths by more than 10% in the small-sample measurements.

Theoretically there are fewer sources of uncertainty in the unit-cell substitution experiments in the ASC than in the small-sample experiments in RSC. First, in the unit-cell substitutions the test zone is a drawer nearly identical with the normal core drawers and consequently the resonance-shielded and hetrogeneous cross sections used in the normal assembly analysis are appropriate for the unit-cell worth analyses. For the small-sample measurements, there is some resonance shielding in the thin samples which is usually neglected. This is an additional source of uncertainty.

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TABLE I. DESCRIPTION OF CONFIGURATION FOR COMPUTATION OF WORTHS OF 1 cm O.D. SAMPLES IN RADIAL SAMPLE CHANGER

Interval	Radius, cm	Reference	Perturbed
1	0.15875	low density 304 SS[a]	low density 304 SS or cylindrical sample
2	0.30	low density 304 SS[a]	low density 304 SS or cylindrical sample
3	0.457	low density 304 SS[a]	low denisty 304 SS or cylindrical sample
4	0.495	low density 304 SS[a]	annular or cylindrical sample
5	0.520	low density 304 SS[a]	low density 304 SS or clad (304 SS)
6	1.176	low density 304 SS[a]	low density 304 SS
7	1.27	sample tube (304 SS)	sample tube
8	2.00	void	void
9	3.00	core material	core material
10	4.00	core material	core material
11	5.00	core material	core material
12	6.00	core material	core material

[a]5% of normal density.

TABLE II. DESCRIPTION OF CONFIGURATION FOR COMPUTATION OF WORTHS OF 2.13 cm O.D. SAMPLES IN RADIAL SAMPLE CHANGER

Interval	Radius, cm	Reference	Perturbed
1	0.50	low density 304 SS[a]	low density 304 SS or cylindrical sample
2	0.80	low density 304 SS[a]	low density 304 SS or cylindrical sample
3	1.027	low density 304 SS[a]	low density 304 SS or cylindrical sample
4	1.065	low density 304 SS[a]	cylindrical or annular sample
5	1.095	low density 304 SS[a]	sample clad (304 SS) or cylindrical sample
6	1.17	sample holder (304 SS)	sample holder
7	1.27	sample tube	sample tube
8	2.0	void	void
9	3.0	core material	core material
10	4.0	core material	core material
11	5.0	core material	core material
12	6.0	core material	core material

[a]5% of normal density.

TABLE III. DESCRIPTION OF PERTURBATIONS FROM WHICH SMALL-SAMPLE WORTHS OBTAINED

Sample	Configuration	Description of Perturbation
MB-10 Pu(1$^{w/o\ 240}$Pu)	L[a]	sample added to interval 4 and clad to interval 5
Pu-9 Pu(11.5$^{w/o\ 240}$Pu)	S[b]	sample added to interval 4 and clad to interval 5
Pu-15 Pu(22$^{w/o\ 240}$Pu)	S	sample added to interval 4 and clad to interval 5
Pu-21 Pu(45$^{w/o\ 240}$Pu)	S	sample added to interval 4 and clad to interval 5
MB-21 Enriched uranium	L	sample added to interval 4 and clad to interval 5
MB-24 Depleted uranium	L	sample added to interval 4 and clad to interval 5
Ta(L) tantalum	L	sample added to interval 4 and clad to interval 5
Ta-2 tantalum	S	sample added to intervals 1 → 4
Mo-1 molybdenum	S	sample added to intervals 1 → 4
Ni-1 nickel	S	sample added to intervals 1 → 4
Fe-1 iron	S	sample added to intervals 1 → 4
Cr-1 chromium	S	sample added to intervals 1 → 4
SS 304	S	clad added to interval 5
B(L) natural boron	S	sample added to region 1
Al(L3) aluminum	L	sample added to intervals 1 → 5
Na(L2) Na	L	sample added to intervals 1 → 4
C(L) carbon	L	sample added to intervals 1 → 5

[a] configuration given in Table II

[b] configuration given in Table I

TABLE IV. COMPARISON OF MEASUREMENT AND CALCULATION FOR SMALL CYLINDRICAL SAMPLES IN ZPR-6 ASSEMBLY 7

Sample	Description	wt., gm.	Specific Worth Ih/kg					
			Normal Plate Core	Central Matched Plate Zone	FOP undistorted,ϕ,ϕ*	FOP distorted,ϕ,ϕ*	EP	EP/FOP
MB-10	Pu($1^{w/o\ 240}$Pu)	9.956	157.9±0.3	157.8±0.3	193.4	189.4	195.5	1.01
Pu-9	Pu($11.5^{w/o\ 240}$Pu)	8.853		143.2±0.3	184.8	181.0	187.5	1.01
Pu-15	Pu($22^{w/o\ 240}$Pu)	8.510		129.0±1.0	168.6	165.2	171.1	1.01
Pu-21	Pu($45^{w/o\ 240}$Pu)	8.508		97.9±0.9	130.5	127.7	132.4	1.01
MB-21	Enriched U	15.775		119.8±0.6	165.6	162.0	164.4	0.99
MB-24	Depleted U	19.074		-11.7±0.6	-13.54	-13.38	-13.46	0.99
TA(L)	Ta	8.698	-58.0±1.5	-58.1	-54.63	-54.02	-53.61	0.98
TA-2	Ta	18.647	-43.1±0.4		-38.58	-37.98	-34.02	0.88
B(L)	Boron	0.5553	-570±12	-570±12	-775.3	-770.7	-750.7	0.97
Ni-1	Ni	37.916	-6.47±0.19		-6.13	-5.74	-5.83	0.95
Fe-1	Fe	33.277	-4.27±0.16		-5.43	-5.19	-5.19	0.96
Cr-1	Cr	26.999	-4.54±0.37		-7.64	-7.33	-7.36	0.96
	SS 304	34.506	-5.03±0.14		-6.11	-5.80	-5.90	0.96
Mo-1	Mo	43.398	-15.39±0.11		-37.78	-37.35	-35.33	0.94
AL(L3)	Al	53.067		-6.83±0.17	-7.83	-7.38	-7.39	0.94
NA(L2)	Na	17.044	-4.73±0.49	-6.21±0.32	-6.09	-5.55	-5.56	0.91
C(L)	C(L)	33.441	-12.19±0.21	-12.67±0.27	-15.87	-14.91	-13.47	0.85

TABLE V. DESCRIPTION OF REFERENCE CELL FOR UNIT-CELL SUBSTITUTION CALCULATIONS
(weights based on 2 × 2 in. plates)

Region	Thickness, cm	Mesh Intervals	Material
1	2.0	2	homogenized core material
2	0.2745	1	matrix steel
3	0.635	2	U_3O_8 (110.104 gm) and SS (6.26 gm)
4	1.27	3	Na (24.883 gm) and SS (31.279 gm)
5	0.3175	1	Fe_2O_3 (37.706 gm) and SS (3.13 gm)
6	0.635	2	Pu/U/Mo (183.401) and SS (20.271 gm)
7	0.3175	1	same as region 5
8	1.27	3	same as region 4
9	0.637	2	same as region 3
10	0.2745	1	same as region 2
11	2.000	2	same as region 1

TABLE VI. DESCRIPTION OF UNIT-CELL SUBSTITUTION PERTURBATIONS

No.	Descriptions	Δk/k, Ih EP
1	Addition of 1.919 gm ^{239}Pu and 1.13 gm of SS to Pu/U/Mo plate	0.4071
2	Addition of 21.155 gm of Pu/U/Mo to Pu/U/Mo plate	0.9549
3	Addition of 14.46 gm of depleted uranium to Pu/U/Mo plate	0.1893
4	Removal of sodium (49.767 gm) from both sodium cans. Sodium-in uranium and plutonium cross sections used in U_3O_8 and Pu/U/Mo plates	0.2675
5	Removal of sodium from both sodium cans. Sodium-out uranium and plutonium cross sections used in U_3O_8 and Pu/U/Mo plates	0.3169
6	1/8 in. Fe_2O_3 plate replaced by void (removal of 37.706 gm of Fe_2O_3 and 3.1299 gm of SS)	0.2683
7	1/8 in. Fe_2O_3 plate replaced by 1/8 in. Fe plate (64.417 gm of Fe substituted for 37.706 gm of Fe_2O_3)	-0.086
8	1/8 in. Fe_2O_3 plate replaced by 1/16 in. SS plate (30.750 gm of SS substituted for 37.706 gm of Fe_2O_3)	-0.0648
9	1/4 in. U_3O_8 plate replaced by 1/8 in. U_3O_8 plate (removal of 55.052 gm of U_3O_8 and 3.13 gm of Fe_2O_3)	0.7249
10	1/4 in. U_3O_8 plate replaced by 1/8 in. depleted U plate and 1/8 in. U_3O_8 plate (150.026 gm of depleted uranium replaces 55.052 gm of U_3O_8)	-1.2675
11	1/4 in. U_3O_8 plate replaced by 1/8 in. U_3O_8 plate and 1/16 in. SS plate (30.75 gm SS replaces 55.052 gm of U_3O_8)	0.5292

TABLE VII. COMPARISON OF MEASURED AND COMPUTED SPECIFIC WORTHS IN UNIT-CELL PLATES IN ASSEMBLY 7

Material	Environment	Specific worth, Ih,kg			
		Exp.	FOP[a]	EP[a]	C/E_{EP}
^{239}Pu	Pu/U/Mo plate	168.7±2.9	205	215	1.27
Pu/U/Mo	Pu/U/Mo plate	32.8±0.4	42.9	45.1	1.37
Depl. U	Pu/U/Mo plate	-8.54±0.44	-12.3	-13.1	1.51
Depl. U	adjacent to 1/8 in. U_3O_8 plate	-8.55±0.09	-12.6	-13.2	1.54
Na	voided sodium cans	-6.68±0.15	-5.40[b]	-5.37[b]	0.80
			-6.37[c]	-6.37[c]	0.95
U_3O_8	1/4 in. plate replaced by 1/8 in. plate	-9.16±0.13	-13.1	-12.8	1.39
Fe_2O_3	1/8 in. plate replaced by void	-6.07±0.28	-6.72	-7.27	1.20
Fe	1/8 in. plate replaced Fe_2O_3 plate	-4.40±0.17	-5.37	-5.27	1.20
SS	1/16 in. plate adjacent to fuel plate	-5.25±0.20	-6.04	-6.01	1.14
SS	1/16 in. plate adjacent to vertical matrix	-5.38±0.37	-5.76	-5.78	1.08

a
χ for Assembly 7 core material based on Keepin data used in generation of undistorted real fluxes. ^{239}Pu χ based on ENDF/B data used in PIT calculation.

b
'sodium-in' cross sections used for plutonium isotopes and ^{238}U.

c
'sodium-out' cross sections used for plutonium isotopes and ^{238}U.

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